REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
October 1996

3. REPORT TYPE AND DATES COVERED
Final 1 April 1995 - 31 October 199

4. TITLE AND SUBTITLE
Optoelectronic Computer Architecture Development for Image Reconstruction

5. FUNDING NUMBERS
61102F
2305/DS

6. AUTHOR(S)
Dr. Richard Forber
Dr. Uzi Efron

AFOSR-TR-97
0303

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research - NE
110 Duncan Avenue, Room B115
Bolling AFB, DC 20332-8080

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-95-C-0030

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

Shear layer turbulence near the surface of an aircraft causes degradation to image quality for on-board imaging sensors looking through this layer. Real-time correction of these images for immediate use by the operators or on-board electronics is of interest. This effort addressed the development of high-speed computational hardware that can perform image reconstruction using turbulence characteristic data. Specifically, we collaborated with UCSD and ERIM on the development of an optically augmented electronic computer for high-speed inverse transform calculations to enable real-time image reconstruction. The joint effort included FFT algorithm assessment and mapping considerations for optically interconnected and enhanced computer architectures (such as the Hughes 3-D computer and possibly multiple FFT/DSP modules), as well as the development (by UCSD) of optical interconnect hardware. The phase-diverse speckle imaging approach developed by the ERIM team was the primary focus of algorithm assessments. Based on projections using next generation DSP and FFT chips, the phase diverse speckle approach was estimated to provide a potential for approximately 30 Hz image reconstruction with 256x256 images. Ongoing effort at UCSD and ERIM will continue to investigate advances of this technology.

14. SUBJECT TERMS

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

19971002 081

DTIC QUALITY INSPECTED 4

Optoelectronic Computer Architecture Development for Image Reconstruction

Introduction

Imaging through turbulence - Real time computational correction

The image quality in parallel image transmission systems is generally degraded by spatial and temporal dispersion of the transmission medium. Many applications ranging from image transmission through turbulence near the skin of an aircraft to wavelength division multiplexed data transmission through fibers, require the compensation of various dispersion effects. The effect of air turbulence on a two-dimensional scene fidelity can be mathematically described as a fourth rank tensor transform (at any instant in time) applied onto the scene data. In order to eliminate the effects of the turbulence on the scene information, an inverse transform must be calculated and applied to the corrupted scene data. To this end, the information related to the turbulence must first be acquired with the appropriate temporal and spatial resolution together with the actual spatially and temporally corrupted scene data. Depending on the requirements of the application, the turbulence characteristic data must be processed in real time for calculating the inverse transform, or it can be stored for off-line processing. The calculated inverse transform must then be applied physically or via software onto the scene data for viewing. With faster time scales and higher spatial resolutions required to model the turbulence effects the data acquisition and required high speed computation can become increasingly challenging.

The effects of the turbulence on the scene data can, in principle, be corrected in real time if the data acquisition and I/O operations to the computer can be performed fast enough. On the other hand a detailed off-line (not real time) analysis of the turbulence requires fast data acquisition and storage on very large capacity memories. This program specifically addressed techniques for real time computational image correction.

Critical components required to recover the scene data in real time are: i) a fast and parallel image and phase front sensing arrays for acquiring the image and turbulence characteristic data, and ii) a highly connected high-speed multi-processor system to efficiently implement the necessary image reconstruction algorithms. In addition, there are constraints on power, size and weight for efficient on-board image processing applications.

In this collaborative effort, we proposed to extend and apply the unique optoelectronic technologies of Hughes and UCSD to this real-time image reconstruction problem. While the Hughes effort is ending with this report, UCSD is continuing under a separate AFOSR contract.

Electro-Optical Computer Architecture (EOCA) - Related DARPA program

A program of related interest, the Electro-Optical Computer Architecture (EOCA) program funded by DARPA, forms the basis for Hughes interest in and support of this reported effort, since the hardware and concepts are much the same. The Aero-optics application is viewed as a valuable practical demonstration of the usefulness and advantages of the 'optically enhanced' computer architecture. Therefore, the EOCA status is briefly reviewed here.

The EOCA program objective is to develop multi-function electro-optic interfaces and optical interconnect units to enhance the performance of parallel processor systems. This program is also performed as a collaboration involving Hughes and UCSD, as well as other institutions. Specifically, three multi-function interface modules—an Electro-Optical Interface (EOI), an Optical Interconnection Unit (OIU), and a Space-Time Compander (STC)—were targeted for development, to be followed by a demonstration of 16x16 subscale prototype for each. The main parallel processor application was the Hughes-conceived (but not realized) 3-D stack architecture, with massive interchip parallel communication using feedthroughs distributed over each chip processor area. Alternative processor architectures are also under consideration, including use of multichip modules (MCMs) based on digital signal processing (DSP) multiple-instruction multiple-data (MIMD) technology (rather than the single-instruction multiple-data (SIMD) 3-D approach).

In 1994, the HRL-UCSD-University of Colorado team successfully integrated a 4x4 Si/PLZT Electro-Optic Interface (EOI) array. Since then, a 16x16 MQW modulator array has been fabricated, integrated with its driver array and demonstrated. The first and second generation of electronic bypass-and-exchange switch array have also been designed, fabricated, and tested for the Optical Interconnection Unit (OIU). In the SpaceTime Compander (STC) development, the team has designed and fabricated the CCD driver circuitry on 19 separate 4-inch Si wafers and has demonstrated the functional operation of the CCD superpixel (8x8 pixel) array. Two compander wafers have now been completely processed. The full demonstration of the three EOCA components in subscale 16x16 arrays is expected by July of 1997. Besides consideration of MCM/DSP-type packages there has been no new development of 3-D-like architectures that would most benefit from the EOCA concept. For more detailed information refer to reports on DARPA contract F30602-93-C-0173.

The EOCA program is presently planned to run through the summer of 1997. To this point, applications of the EOCA hardware within Hughes programs have not been of enough business interest to justify continued development investment at HRL. This is not to discourage its continuation by UCSD and other institutions, but there are no plans at this time to continue the effort within Hughes after the end of the DARPA-funded EOCA program.

Brief Statement of Work - This effort

Four tasks were identified in a joint program between HRL and UCSD. The first task involves the specific relationship to the imaging through turbulence problem and addresses the computational algorithms for the proposed computer architecture. The second and third tasks focus on specific hardware developments by UCSD for the optical interfacing components. The fourth task offers considerations for alternate electronic computer architectures that might be used in place of the Hughes 3-D processor concept.

Task 1. Study adaptive filters and associated algorithms, and their mapping onto the proposed computer architecture. This task had three components:

a) Identify appropriate techniques for data acquisition on shear layer turbulence that support parameters needed in algorithms for dynamic computational image reconstruction.
b) Determine and assess appropriate software algorithms which relate to measured input parameters as well as to the optoelectronic computer architecture being proposed;
c) Establish details of algorithm mapping to the proposed EO computer architecture.

(Task 1 relied on data and inputs, as in the Technical Proposal from AOA (ref. Feb. '95 revised proposal 95M-0048/K1465-1 from Hughes), to be supplied by AFOSR, or designees. UCSD and ERIM will continue providing this effort.)

Task 2. Develop a very high speed optoelectronic computer interface using MQW modulators.

(This task performed under separate contract to UCSD. HRL to assist as necessary.)

Task 3. Improve packaging of the optical interconnection unit based on the Optical Transpose Interconnection System (OTIS) by development of the Birefringent Computer Generated Holography (BCGH) approach.

(This task performed under separate contract to UCSD. HRL to assist as necessary.)

Task 4. Investigate alternatives to the Hughes 3-D processing element architecture for incorporation of the above optical technologies. In particular, explore the use of multi-chip modules (MCMs) composed of high-speed digital signal processing (DSP) elements.

(This task continued by UCSD.)

Accomplishments

Overview

This program effort was performed in conjunction with UCSD with collaborative input also from the Environmental Research Institute of Michigan (ERIM), both under separate contract from AFOSR within the Aero-optics and Image Reconstruction initiative. The algorithm assessment required data and inputs on relevant image reconstruction algorithms and algorithm mapping, a role originally planned for Adaptive Optics Associates (AOA) as subcontract to Hughes, but changed at AFOSR's request (with reduction of equivalent funds to Hughes) to designees of AFOSR, such as ERIM and UCSD. The ERIM phase-diverse speckle algorithm assessment and mapping was a primary focus in algorithm mapping. The optical interconnect component development was performed entirely by UCSD, and is detailed in their reports. Investigations of alternative hardware to the Hughes 3-D SIMD concept centered on considering multi-chip modules of DSP and FFT chips, which may be well suited to the FFT-intensive ERIM algorithm, but other possibilities may exist that are better. UCSD is continuing this investigation.

Task 1 - Algorithms

The HRL-UCSD teams collaborated with the ERIM team on the phase-diverse speckle algorithm for iterative image reconstruction, which is FFT computation intensive. Thus, we have also focussed on FFT-specific processors as the heart of the opto-electronic architecture, with multiple DSPs for complementary processing. There may be other bottlenecks (besides FFT calculations) with regard to practical image reconstruction with this approach, and it may be possible to alleviate some bottlenecks by use of optical interconnection between input devices, processors, and memory.

A discussion of the progress on algorithm mapping by the Hughes-UCSD-ERIM joint effort has also been described in the UCSD Annual Report for September 1996, and was presented at the AFOSR Aero-optics review in Atlanta September 4, 1996.

The phase-diverse speckle (PDS) algorithm

In the phase-diverse speckle approach [J. Seldin and R. Paxman, SPIE Vol. 2302, 268-280 (1994)] the process starts by collecting in parallel one aberrated image (otherwise 'in focus') and one, or more, intentionally out-of-focus aberrated image(s) for a series of different aberration realizations. By an iterative process one obtains both the object data and the estimated sequence of phase aberrations. The algorithm is based on maximization of the (modified) log-likelihood function, L. The L evaluations are dominated by FFTs, which need to be computed in a sequential

fashion in the search for maximization. Each gradient line search in the maximization involves 5 to 10 L evaluations, and as many as 50 iterations (or 50 gradient evaluations) are needed for the overall L maximization. Once the maximization is complete the object data is obtained by deconvolution, and the process begins again with a new sequence of images.

Assumptions

We have used the goal of 256x256 images, with 12 bit pixel depth, at restoration rates of 30 Hz, or better. With a turbulence time scale of ~100 μsec, image data must be acquired at ~10 kHz, which means hundreds of images (diversity sets) would be acquired per restoration, not all of which are used. In fact, using only 5 diversity sets per frame, with only 1 pair per set (each pair having a different aberration realization), acceptable image restoration can be obtained, and is assumed sufficient here. The discarded data is not a problem when image content is not significantly changing over the video frame time.

It is also assumed that the aberrations are space-invariant over the image, so that they are the same for all points in the 256x256 field of view. With the PDS algorithm it is possible to obtain acceptable estimates of the aberrations on as little as a 64x64 patch within the full image. It is estimated that 50 iterations in the PDS inner loop will produce acceptable results in the object data and phase aberration determination. It is also assumed that the image deconvolution can be performed in parallel with the next frame image restoration, resulting in a modest latency that can be tolerated.

Unfortunately, there is no 3-D SIMD element available as the central processor in the optoelectronic computer architecture. We presently plan instead for use of multi-chip modules (MCMs) with DSPs together with advanced FFT chips. For optical interconnects, this means no massively parallel interchip communication—only interconnects along the card edges, which impacts interchip communication time to an extent still to be determined. The FFT chips could use optics for both I/O and chip-to-chip interconnects. Projected next-generation FFT-specific chips (called VFFTs) have performance of ~8 μsec for a 1-D, 1K-point FFT.

Performance estimation:

The performance of the PDS algorithm within the proposed hardware approach is broken down into three parts: (i) image acquisition, (ii) image reconstruction by iteration, and (iii) object data deconvolution (image restoration), as illustrated in Fig. 1. Image acquisition by CCD devices should be possible with 100 μs acquire time and 1 msec frame readout time; with use of 5 diversity pairs that amounts to 5 msec. The bottleneck occurs for the iterative image reconstruction

which has several steps that must be performed in series, though the 5 diversity pairs (10 images) can be handled mostly in parallel within each iteration by use of 10 parallel processing blocks (as illustrated). Each iteration is composed of multiple 4K-FFTs, multiple pointwise calculations, multiple accumulate steps, and a new search direction computation, all of which occur mostly in series over approximately 0.5 msec. Assuming 50 iterations are needed this amounts to about 25 msec. The object data deconvolution is performed after the PDS algorithm has determined all the phase aberration parameters, resulting in image restoration free of the aberration blur. A preliminary estimate for the deconvolution time is approximately 10-20 msec, but since this can be performed with a separate compute module it is performed during the next frame image reconstruction. Thus, there will be a scene-to-restoration latency of approximately 40-50 msec.

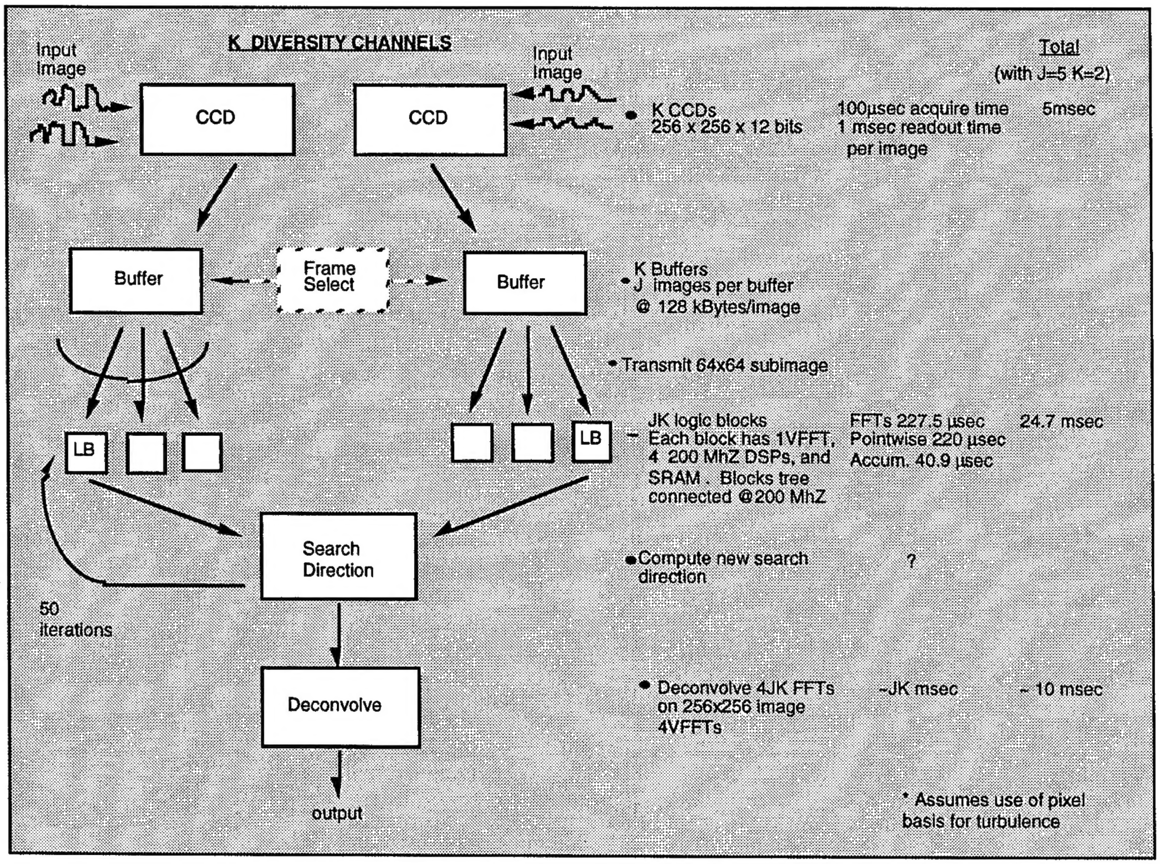

Fig. 1. Schematic diagram of the image restoration system. (From UCSD 9/96 AFOSR review)

From these estimations we conclude that video rate image reconstruction may be possible under the assumptions discussed above. There are some noted factors yet to be quantified, and a hardware implementation relies on development of high-speed image acquisition devices, fast FFT chips, appropriate packaging and interconnection, and possibly more modifications to this preliminary analysis.

Suggestions for continued effort:

1. Develop a computer emulation of the diversity algorithm solution of image reconstruction within the EOCA-type architecture. Thus, new ideas on how to carry out the implementation can be tested with better insight.
2. Make use of a better understanding of the image distortion (caused by shear-layer turbulence) to guide innovative solutions in the algorithm implementation.
3. Coordinate with other teams on specifics of the turbulence parameters to be measured for input to the algorithms. Appropriate hardware data acquisition (sensors/optics) must match the needs of the algorithms.
4. Consider a hardware demonstration to verify predictions.

UCSD and ERIM are expected to continue the study of algorithms and their mapping onto the proposed optoelectronic computer architectures, as well as other computing platforms deemed appropriate.

Task 2 - MQW-based optoelectronic interface

This effort is being performed by UCSD (ongoing). For current progress and status of this development you are referred to the UCSD annual reports under Grant F-49620-95-I-0289.

Task 3 - Birefringent holograms/OTIS

This effort is being performed by UCSD (ongoing). For current progress and status of this development you are referred to the UCSD annual reports under Grant F-49620-95-I-0289.

Task 4 - Alternative architectures for the EOCA processor

The EOCA, as it was initially conceived, is an ideal adjunct to high performance processors that are of the fine grain, Single Instruction-Multiple Data (SIMD) family of architectures. The EOCA offers significant performance enhancements to these systems that otherwise rely on conventional wiring for inter-processor communication. The fine grain, SIMD architectures, such as the 3-D computer concept, because of the massive numbers of processors (>10,000) are implemented using bit serial processors. This is in contrast to the traditional uni-processors found in desktop computers and workstations and the MIMD architectures which employ bit parallel processors (e.g., 16 bit, 32 bit, etc...). This switch from a bit serial data format to bit parallel is one of the two major issues in attempting to apply the EOCA to high performance MIMD architectures.

The second major issue in applying EOCA technology to MIMD processors is the physical size of a typical MIMD processor and its coupling with an optical system. Each node of a MIMD system will require a significant quantity of hardware for implementation. While these hardware components at each node will be packaged as compactly as is feasible, the physical size of each node is expected to be at least several tens of cm^2. Each node will have of the order of 100 I/Os, most likely distributed in an irregular pattern. The resultant physical density of the I/O (> 0.5 cm^2/I/O) will be ~200x larger than that originally envisioned for EOCA as an augmentation to the 3-D computer concept.

MIMD architectures can be implemented in a variety of VLSI architectures including DSP's or FPGA chips. The use of Multiple-Chip-Modules (MCMs) as a packaging method with VLSI circuits (such as FPGA's or DSP's), rather than the Hughes 3-D computer concept, is a significant departure that requires further evaluation. One possible packaging alternative is the use of 'quasi 3-D' packaging being offered by Irvine Sensors; however, this technique establishes chip contacts only along the edges of the stack so that full interchip communication requires added looping through the stack.

In addition to the issues involving the compatibility of the MCM /Multi-DSP's architectures to that of the EOCA, it is also necessary to consider the suitability of any new platform to the image reconstruction algorithm implementation.

Finally, even though the SIMD architecture has been only slowly developing in the past few years, it should not be completely discarded as it still is best suited for the implementation of the EOCA architecture and is very powerful for the parallel implementation of image reconstruction algorithms. Since the computational problem is related to the computer vision problem, one could potentially take advantage of several recent SIMD implementations of computer vision in VLSI parallel processor array architectures.

The present computing platform under consideration by the UCSD team is based on a multi-module approach with each module containing one VFFT chip, four 200 MHz DSP's and four 1 Mbyte SRAMs, with 64-bit wide buses interconnecting the modules. Other possibilities may be considered as the program evolves at UCSD.

Conclusions and Summary

The ERIM phase-diverse speckle algorithm was investigated, mapping issues were addressed, and preliminary near-term performance was assessed. It's projected that real time (~30 Hz) image reconstruction is possible for 256x256 image size (12 bit pixel depth) based on next generation

VFFT hardware. Some aspects of the mapping remain to be done, and the advantages of symmetries, parallelism, and simplifications could yield further performance benefits.

Next-generation FFT and DSP chips were the basis of hardware applications of the optical enhancements and algorithm evaluations in this joint investigation, so far. Performance limitations compared to the original 3-D computer concept are still to be determined. Interchip communication and optical interconnections are still to be addressed, and will be investigated by UCSD.

Over the past year Hughes involvement in, and support of, related 3-D opto-electronic computer technology has unfortunately declined—a situation which impacts this program. It was hoped that replacements to the 3-D could and would have been pursued that add value to this effort, and the general EOCA approach as well. As it is likely that other Aero-optics investigations elsewhere can offer more benefit to this initiative, the Hughes participation in the joint effort is being discontinued by mutual Hughes-AFOSR agreement.

Personnel Supported/Associated with Effort

Dr. Richard Forber and Dr. Uzi Efron of Hughes Research Laboratories, Malibu, CA are the primary persons from HRL on this program. Dr. David Shu, Dr. David Schwartz, and Dr. C.S. Wu, also of Hughes Research Laboratories, are associated with the EOCA and image reconstruction efforts, and consult as needed.

Prof. Sadik Esener, Prof. Shaya Fainman, Dr. Philippe Marchand and Mr. Francis Zane of the University of California at San Diego, CA, are all associated with this effort--supported by a separate AFOSR contract under Grant F-49620-95-I-0289. Dr. Richard Paxman and Dr. John Seldin of the Environmental Research Institute of Michigan (ERIM) are also associated with this effort in Task 1.

Hughes completed approximately 25% of the planned 1 person-year total effort. The program is being discontinued at the midpoint of the 3 year planned period of performance.

Publications

P. Marchand, A. Krishnamoorthy, G. Yayla, S. Esener, and U. Efron, "Optically Augmented 3-D Computer: System Technology and Architecture," submitted to the Journal of Parallel and Distributed Computing, Special Issue on Optical Interconnects, December 1995.

For a list of other publications relevant to the Hughes-UCSD joint effort please refer to the UCSD reports under Grant F-49620-95-I-0289.

Interactions/Transitions

Consultative/Advisory

HRL has had ongoing collaboration with UCSD in the area of advanced Electro-Optical Computer Architecture development (DARPA/Rome Laboratory Contract No. F30602-93-C-0173), as well as this program. The EOCA collaboration was viewed as an essential basis to the goals of the program reported herein. We have also consulted and collaborated with Dr. Richard Paxman and Dr. John Seldin of the Environmental Research Institute of Michigan (ERIM) in regards to applying the phase-diverse speckle algorithm to this optoelectronic computer architecture.

UCSD has been fully involved in this collaboration and will continue in this algorithm investigation, as well as the optical interconnect component development. For a list of UCSD presentations and transitions relevant to this joint effort refer to the UCSD reports under Grant F-49620-95-I-0289.

Discoveries/Inventions/Patents

None.

Honors/Awards

None.